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Electricity generation from a solar parabolic concentrator coupled to a thermoelectric module

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Abstract

The concept of generating electricity from the sun's energy using a parabolic concentrator and a thermoelectric (TE) module is presented in this study. The proposed TE solar concentrator was composed of a parabolic dish collector with an aperture of 1.5 m that was used to concentrate sunlight onto a receiver plate with an area of 10 × 10 cm^2. One BiTe-based TE module installed on the receiver plate was used to convert the concentrated solar thermal energy directly into electric energy. A rectangular fin heat sink coupled with a fan was used to release heat from the cold side of TE module and a tracking system was used to continuously track the sun. The effects of fan orientation and air flow rate were investigated. Under maximum heat flux, the TE module was able to produce 1.32 W at 0.42 m^3/min of the air flow rate (pushing air), corresponding to 2.89% conversion efficiency. The proposed concept seems to be reliable and merits further investigation.

Keywords: Electric energy, Conversion efficiency, Solar thermal energy

1. Introduction

Thailand is located in the tropical region. An 8-year period (1995-2002) of satellite data was used to generate a direct normal radiation map of the country [1]. The map reveals that the areas receiving the

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highest radiation are mainly located in the Northeast and the Central regions of the country, with the yearly sum of direct normal radiation in the range of 1350-1400 kWh/m^2. The annual direct normal radiation received in most parts of Thailand is large when compared to other parts of the world. Concentrating solar power (CSP) systems can be used effectively to convert solar energy into electrical energy. The CSP systems, namely, parabolic through, liner Fresnel reflector, power tower and parabolic dish are capable of producing power. Among the CSP technologies, the parabolic dish collector is recognized as the most efficient system for energy conversion. The successful implementation of any new technology depends on the cost efficient conversion of energy. The cost of a solar collector field is determined primarily by it size, while the cost of the energy production depends on both the collector field cost and the amount of the energy collected by the dish system. One way to increase solar energy conversion is by decreasing the amount of shadow falling on the adjacent dish. The economic viability of the system depends on design and configuration. The configuration of the dish field has to be based on minimum interference/shading of one dish on another so that land utilization is maximized.

The thermoelectric (TE) generator is a solid state direct energy converter using the principle of the Seebeck effect. It has special features like the absence of moving parts, compact size, silent operation, high reliability, and it does not produce any greenhouse gas emissions during operation [2]. In addition, due to its operation at elevated temperatures the TE generator is attractive for applications that involve a solar concentrating collector. Research on TE energy conversion with flat plate solar thermal collectors, such as Chen [3], derived a thermodynamic analysis of a solar-driven TE power generator based on a well-insulated flat plate collector. In Chen's study a thermodynamic model including four irreversibilities was used to investigate the optimum performance of a solar-driven TE generator. The example discussed by Chen is based on an extremely well-insulated flat plate collector, which, in practice, may be difficult to achieve. Rockendorf et al.[4] constructed a prototype of a solar thermoelectric water heater in which the hot side of a TE module was heated by solar hot water. The heat was released at the cold side of TE module via a heat sink. Three vacuum-tubes with heat pipes each with a 0.1 m^2 absorber area and with water as the heat pipe medium were connected via a specially designed heat exchanger to a fluid circuit acting as a heat sink. Test result showed that the electrical efficiency reached a maximum value of 1.1% of the incoming solar radiation, which is approximately 2.8% of the transferred heat. Scherrer et al.[5] presented a series of mathematical models based on the optimal control theory to assess the electric performance of a skutterudites-based solar TE generator as a function of sun-spacecraft distance. The design parameters (such as dimensions, weight and so on) were optimized for operating at a distance of 0.45 a.u. from the sun with 400 W electrical output power and a required load voltage of 30 VDC. The simulation results indicated that the skutterudites-based solar TE generator offered attractive performance features as a primary or auxiliary power source for spacecraft in near-Sun missions. Maneewan et al. [6] studied a thermoelectric roof solar collector (TE-RSC) to reduce roof heat gain and improve indoor thermal comfort. Maneewan's TE-RSC combined the advantages of a roof solar collector and TE generator to act as a power generator. The electric current produced by the TE modules was used to run a fan for cooling the modules and improve the indoor thermal conditions. The subsequent simulation results, using a real house configuration, showed that a TE-RSC unit with a surface area of 0.0525 m^2 could generate about 1.2 W under solar radiation intensity of about 800 W/m^2 and at ambient temperatures varying between 30 and 35°C. The induced air change rate varied between 20 and 45 ACH (Number of air changes per hour) and the corresponding ceiling heat transfer rate reduction was about 3-5 W/m^2. The electrical conversion efficiency of the TE-RSC system proposed in this study is 1-4%. Kraemer et al.[7] presented a high performance flat-panel solar TE generator by using high thermal concentration (The area of the absorber plate divided by the cross-sectional area of the thermoelectric elements). The efficiency is seven to eight times higher than the conventional solar TE generator. According to literature reviews, solar TE generators convert a few percent of the entire incoming solar

radiation into electricity. More than 90% of the incident solar radiation on a TE is reflected or converted to thermal energy. In order to increase the electrical and thermal output of the TE solar collector, reflectors are used to concentrate the solar radiation to the surface of the collector. A few research works reported on a TE generator with a solar concentrating collector. As an example, Fan et al. [8] investigated a parabolic dish concentrator TE generator. A parabolic dish collector with an aperture of 1.8 m was used to concentrate sunlight onto a copper absorber plate. Four BiTe-base TE modules were used to convert the concentrated solar thermal energy directly into electric energy. A water cooled heat sink was used to remove waste heat from the cold side of the TE modules. Experimental results showed that the concentrator TE generator was able to produce electric power of up to 5.9 W for a 35°C temperature difference with a hot side temperature of 68°C. Lertsatitthanakorn et al. [9] studied a double-pass TE solar air collector with flat plate reflectors. The flat plate reflectors were used to concentrate solar radiation onto the TE solar air collector. Experimental results showed that the optimum position of the reflectors was 60°, which gave significantly higher thermal energy and electrical power output than the TE solar collector without reflectors. This article presents the performance of a solar parabolic concentrator coupled to a TE module. The effects of air cooling, flow rate and fan orientation are investigated.

Nomenclature

A	area of the solar collector (or reflector)
C_{pa}	specific heat at the average air temperature
I	maximum current of the TE modules at a matched load.
I_b	beam solar radiation
m_a	air mass flow rate
T_{aco}	air temperature at the outlet of heat sink
T_{amb}	ambient temperature
T_e	temperature of boiling water
T_m	average temperature
V	maximum voltage of the TE modules at a matched load
ρ_a	reflectance of the reflective material. (0.85 for aluminium foil)
Z	figure of merit of the TE material. (Z=1.6 × 10^{-3} 1/K)

2. System DescriptionandExperimental Method

Fig. 1 shows a pictorial view of the solar parabolic concentrator coupled to TE module. The system consists of a parabolic dish concentrator (collector), one TE module, a linear one-axis tracking system, and a heat transfer system (absorber plate and air cooled heat sink). The dimensions of the parabolic dish are presented in Fig. 2.

Fig. 1.Photograph of the solar parabolic concentrator coupled to TE module.

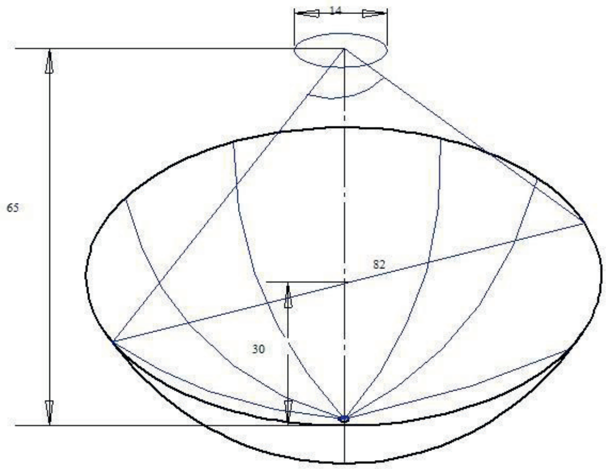
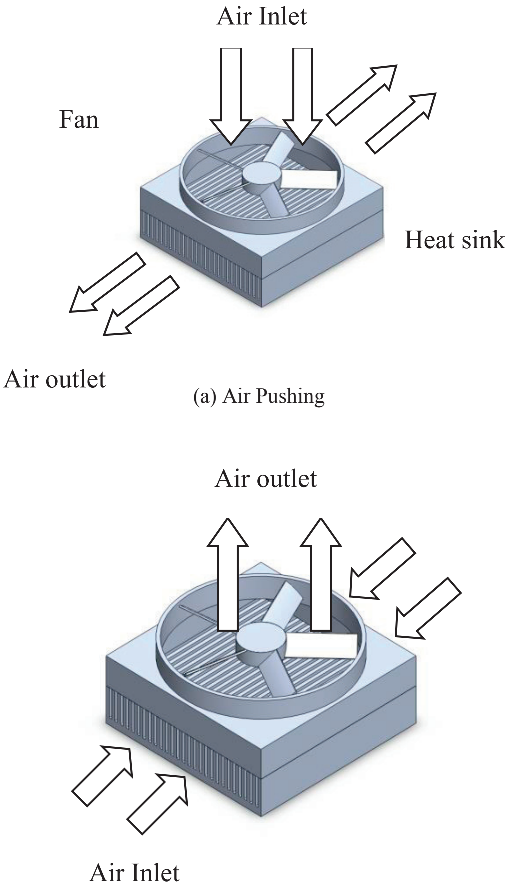


Fig. 2.Dimensions of the parabolic dish (All dimensions are in mm)

The parabolic dish was constructed from eight parabolic segments of steel with an overall aperture of 1.5 m and a focal length of 0.65 m. The concave face of the concentrator was lined with a highly reflective material. It should be noted that the size of the absorber plate is quite small compared with the reflector area; therefore, the profile and reflectance of the concentrator are very important to ensure that maximum incoming solar energy is reflected onto the absorber plate. Geometrical measurements were taken to establish the profile of each dish segment. Of the material available in a local marketplace, aluminum foil (85% reflective) was chosen due to its high reflectivity and availability at low cost. The

absorber plate temperature must be less than 200°C. For temperatures in this range, Bi2Te3 based materials are the most suitable [10]. As such, commercial TE cooling modules by Melcor were used in this work. Each module, with a size of 40 mm × 40 mm × 3.5 mm, has a matrix of 127 TE couples (p-type and n-type). In the current application one TE module was sandwiched between the back side of the absorber plate and an air cooled aluminum fin heat sink with a brushless fan. Moreover, in order to minimize the thermal contact resistance, a layer of heat conductive silicone grease was applied to all the contact surfaces. A schematic diagram of the TE generator system is shown in Fig. 3.



(a) Air Pushing

(b) Air pulling

Fig. 3A schematic diagram of the TE generator system.

Fig. 1 also shows the TE generator system as placed in the focal area of the parabolic concentrator. The solar parabolic concentrator coupled to the TE generator was mounted on a one axis tracking base. Tracking of the sun was done manually.

In this study, the effects of fan orientation, namely, air either being pushed or pulled through the fin heat sink (see Fig. 4), and the air flow rate on the performance of the TE generator were assessed.

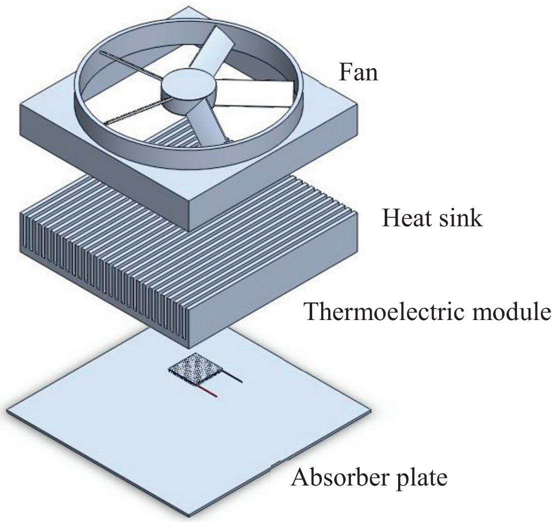


Fig. 4Fan orientation.

The TE generator system was instrumented with T-type (accuracy ±0.5°C) thermocouples at the hot and cold sides of the TE module and heat sink. The thermocouple that measured ambient temperature was kept in a shelter to protect the sensor from direct sunlight. A normal-incidence pyrheliometer (Eppley accuracy ±10 W/m^2) was used to measure the direct solar radiation. The air flow rate was calculated from the air velocity, measured by a hot wire anemometer (Testo model 445, accuracy ±0.03 m/s). The output current and voltage were measured with a multi-meter (Fluke model 189, accuracy VDC ±0.025%, A ±0.5%). Experimentation started at 9 a.m. and ended at 4 p.m.

3. Calculating Methods

The incoming solar radiation incident (S) on the absorber plate is

$$S = A_c \rho_a I_b \tag{1}$$

The total heat dissipated by the cooling air (Q_t), which can be obtained by using Eq. (2) as

$$Q_t = m_a C_{pa} \left(T_{aco} - T_{amb}\right) \tag{2}$$

The electrical output of the TE solar collector (P) is calculated from the measured data as follows:

$$P = I \cdot V \tag{3}$$

The heat transfer efficiency (η_t) is calculated by relation:

$$\eta_t = \frac{Q_t}{S} \tag{4}$$

Miller et al. [11] suggested that the conversion efficiency (η_e) is as follows

$$\eta_e = \eta_c \frac{M - 1}{M + \frac{T_c}{T_h}} \qquad (5)$$

where$M = \sqrt{1 + ZT_m}$ which $T_m = 0.5(T_h + T_c)$

Note that ZT_m is a characteristic parameter of the thermoelectric element and essentially governs its internal conversion efficiency. It is well known that the value of Z can have strong variations in temperature. In this study, in order to gain insight into the optimal collector operating temperatures, the value of Z is assumed to be constant. Although this may be an over simplification of the actual situation, it provides tractable solutions for the solar collector temperature and operating efficiency of the thermoelectric element.

$\eta_c$is the Carnot efficiency; $\eta_c = \frac{T_h - T_c}{T_h}$ (6)

4. Results and Discission

Testing the performance of a solar parabolic concentrator coupled to a TE generator was performed during December 2012 and January 2013. Data reported here were selected from days with relatively similar ambient conditions that permitted a subjective comparison.

4.1. Effect of fan orientations

Two fan orientations were evaluated; air was either pushed or pulled through the finned area. The performance of the solar parabolic concentrator coupled to the TE generator is dependent on energy delivered by the parabolic concentrator to the TE hot junction. A plot of power output against direct solar radiation (Fig. 5) shows that as the solar radiation increased, the power output increased exponentially. Based on the measurement results, higher output power was recorded when the air was pushed through the fins.

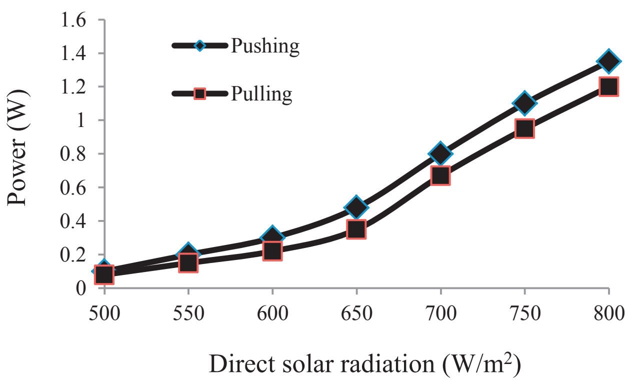


Fig. 5Power output versus direct solar radiation (0.42 m^3/min of air flow rate)

A possible explanation for the differences in performance between pushing and pulling air is the trade-off between turbulence at the expense of decreased air flow. It is thought that the pushing air caused turbulence at the base of the fins; whereas, when the fin was pulling the air, little turbulence was created at the base of the heat sink [12]. Turbulence tends to enhance heat transfer, but it also causes a significant pressure drop. Consequently, both the heat transfer and the conversion efficiencies of the pushing air were more than the pulling air by 6% and 12.8%, respectively. Thus, pushing air through the heat sink is recommended.

4.2. Effect of air flow rate

The effect of air flow rate pushing through the heat sink at the cold side of the TE module is shown in Fig. 6. Tests were conducted at three different air flow rates namely: 0.26, 0.35 and 0.42 m^3/min. It can be seen that the cold side temperature decreased as the air flow rate increased, and more heat was ejected to the ambient air.

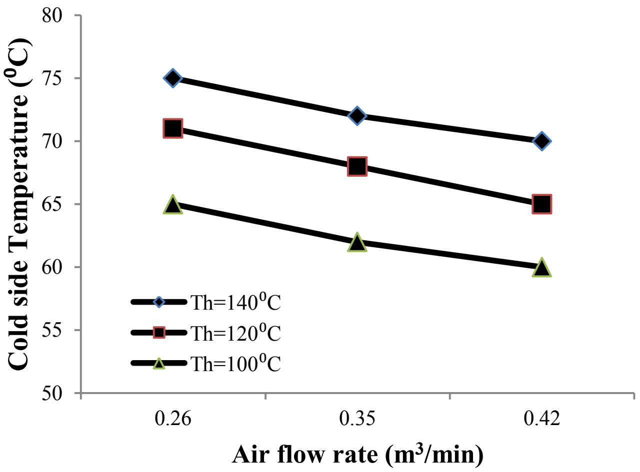


Fig. 6Cold side temperature versus air flow rate. (Th = the hot side temperature of the TE module).

Therefore, the power output (P), heat dissipated by the cooling air (Q_t), heat transfer (η_t) and conversion (η_e) efficiencies increased as the air flow rate increased as shown in Table 1. Consequently, a high air flow rate is recommended which should be considered depending on the efficiency of the heat sink used.

Table 1.Effect of air flow rate on power, heat dissipated by the cooling air, heat transfer and conversion efficiencies.

Item	Air flow rate (m^3/min)		
	0.26	0.35	0.42
P (W)	0.88	1.18	1.32
Q_t (W)	74.5	77.2	95.1
η_t (%)	6.4	6.6	7
η_e (%)	2.64	2.82	2.89

5. Conclusions

The concept of combining a parabolic dish concentrator with a TE module to produce electricity and thermal energy from the sun was explored with a simple prototype and some preliminary experimental measurements. Air pushed through the heat sink was found to be more efficient than air pulled through the heat sink. A high air flow rate proved better than the low air flow rate. It was found that the solar parabolic concentrator coupled to TE generator can produce a maximum power output of 1.38 W at 0.42 m^3/min of the air flow rate (pushing air). Further optimization based on thermal concentration (The area of the absorber plate divided by the cross-sectional area of the thermoelectric elements) is planned.

Acknowledgements

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